PB90-265026

Modeling the Transport of Fine-Grained Sediments in Aquatic Systems

California Univ., Santa Barbara

Prepared for:
Environmental Research Lab.-Duluth, MN

1986

U.S. Department of Commerce
National Technical Information Service
NTIS

TECHNICAL REPORT DATA
(Please read Instructions on the reverse before complet

1. REPORT NO.	2.	3.
EPA/600/J-86/544		PB90-265026

4. TITLE AND SUBTITLE	5. REPORT DATE
Modeling the Transport of Fine-Grained Sediments in Aquatic Systems	6. PERFORMING ORGANIZATION CODE

7. AUTHOR(S)	8. PERFORMING ORGANIZATION REPORT NO.
Lick, Wilbert	

9. PERFORMING ORGANIZATION NAME AND ADDRESS	10. PROGRAM ELEMENT NO.
Department of Mechanical Engineering, University of California, Santa Barbara, CA 93106, USA	11. CONTRACT/GRANT NO. Grant 811578 RPT 1174

12. SPONSORING AGENCY NAME AND ADDRESS	13. TYPE OF REPORT AND PERIOD COVERED
Environmental Research Laboratory Office of Research and Development U.S. Environmental Protection Agency Duluth, Minnesota 55804	14. SPONSORING AGENCY CODE

15. SUPPLEMENTARY NOTES

Published in The Scienc of The Total Environment, 55 (1986) 219-228

16. AESTRACT

Recent work on the understanding and numerical modeling of the transport of fine-grained sediments in near-shore areas of lakes, estuaries, and oceans is discussed. The presentation is concerned not only with the transport of sediments in the overlying water but also with the interactions between the bottom sediments and the overlying water. In particular, a quantitative model of the entrainment and deposition of fine-grained sediments is proposed.

17. KEY WORDS AND DOCUMENT ANALYSIS

a. DESCRIPTORS	b. IDENTIFIERS/OPEN ENDED TERMS	c. COSATI Field/Group

REPRODUCED BY
U.S. DEPARTMENT OF COMMERCE
NATIONAL TECHNICAL
INFORMATION SERVICE
SPRINGFIELD, VA 22161

18. DISTRIBUTION STATEMENT	19. SECURITY CLASS *(This Report)*	21. NO. OF PAGES
		10
	20. SECURITY CLASS *(This page)*	22. PRICE

PB90-265026

EPA/600/J-86/544

The Science of the Total Environment, 55 (1986) 219—228
Elsevier Science Publishers B.V., Amsterdam — Printed in The Netherlands

MODELING THE TRANSPORT OF FINE-GRAINED SEDIMENTS IN AQUATIC SYSTEMS

Wilbert Lick
Department of Mechanical Engineering, University of California, Santa Barbara, California 93106, USA

ABSTRACT

Recent work on the understanding and numerical modeling of the transport of fine-grained sediments in near-shore areas of lakes, estuaries, and oceans is discussed. The presentation is concerned not only with the transport of sediments in the overlying water but also with the interactions between the bottom sediments and the overlying water. In particular, a quantitative model of the entrainment and deposition of fine-grained sediments is proposed.

INTRODUCTION

Many of the waste products generated by man are frequently discharged into near-shore areas of lakes, estuaries, and the oceans. Among these are industrial wastes, dredged sediments, sewage effluents, sewage sludge, oil spills and drilling muds from offshore oil exploration, and resuspended bottom sediments during dredging and mining operations. Many of these wastes are toxic and their disposal is becoming of increasing importance to mankind.

After being introduced into the water, most of the contaminants are adsorbed to fine-grained particles while the rest exist in the dissolved state. The contaminants adsorbed on particles are dispersed by wave action and currents, then deposited on the bottom, and later resuspended and again dispersed by wave action and currents; a series of events which continues until the contaminants are transported out of the system or until they become a permanent part of the bottom sediments. During resuspension, finer particles may aggregate to form larger particles (flocculation) and larger particles may disaggregate into smaller particles with the rates of aggregation and disaggregation dependent on the turbulence, particle concentration, particle sizes, and other factors. These physical processes are accompanied by complex chemical and biological processes which alter the contaminants and which occur in the bottom sediments as well as in the water column. It should be emphasized that bottom sediments are a major repository of contaminants and serve as a highly variable source or sink for contaminants in the overlying water depending on (a) resuspension and deposition of bottom sediments due to

0048-9697/86/$03.50 © 1986 Elsevier Science Publishers B.V.

NTIS is authorized to reproduce and sell this report. Permission for further reproduction must be obtained from the copyright owner.

currents, tides, and wave action, (b) benthic activity, and (c) chemical diffusion.

In order to adequately evaluate disposal alternatives, the transport and fate of contaminants must be determined quantitatively. Recent work on chemical and biological processes of significance in water pollution has been reviewed elsewhere (refs. 1,2). Because of this and because of the importance of fine-grained sediments in the transport of contaminants, the emphasis here will be on the understanding and modeling of the transport of fine-grained sediments in the overlying water and the interactions between the bottom sediments and the overlying water. In this context, essential processes that must be understood are: (1) particle sizes, settling speeds, and the rates at which particles aggregate and disaggregate; (2) the net flux of sediment at the sediment-water interface due to entrainment and deposition; and (3) the hydrodynamics as caused by wave action and currents and as described by the fluid velocities and the diffusivities. These processes are discussed in detail below.

Much of the discussion will be based on research concerned with the Great Lakes and Long Island Sound in North America, all of which are relatively shallow bodies of water. A more immediate application is to the transport and fate of contaminants in the Venice Lagoon, an extremely shallow body of water with an average depth of about 1m and with a surface area of approximately 500 $km.^2$

PARTICLE SIZES, SETTLING SPEEDS, AND FLOCCULATION

A knowledge of particle sizes, settling speeds, and the effects of aggregation on these parameters is important in determining settling speeds, deposition rates at the sediment-water interface, and the release of contaminants from aggregated particles to the surrounding waters. In most work on these problems, it has been assumed that sediments can be described in terms of average quantities, e.g., an average settling speed. Although this is a valid first approximation, it should be realized that sediments consist of a mixture of particles of highly variable size and composition.

For a typical sediment, particle sizes may vary over two to three orders of magnitude while settling speeds may vary by more than four orders of magnitude. If a particle is spherical with known density, the size and settling speed are related by the well-known Stokes' law, which is

$$w_s = \frac{gd^2}{18\mu} (\rho_s - \rho) \qquad (1)$$

where g is the acceleration due to gravity; d is the diameter of the particle; ρ_s is the density of the particle; ρ is the density of water; and μ is the

molecular viscosity of water. The formula is valid for settling speeds such that the Reynolds number ($Re = \rho w_s d/\mu$) is less than about 0.5, i.e., for sedimentary particles (with ρ_s about 2.65 gm/cm^3) with a diameter less than about 100 μm.

However, most particles are not spherical and, more than that, individual particles tend to aggregate together into flocs, groups of particles more or less tightly bound together. From recent experiments (ref. 3), it can be shown that in these flocs individual particles (about 1 μm in diameter) are relatively closely and therefore strongly bound together into clumps. Several of these clumps are then loosely and therefore relatively weakly bound to each other to form a floc. Because of this aggregation, the diameter and settling speed of a floc are not related by Stokes' law but depend on the state of aggregation. Each parameter must therefore be determined independently.

The formation of flocs is a dynamic process with the state of aggregation at any particular location and time depending on the rates of aggregation and disaggregation. The rate of aggregation depends on the rate at which particles collide and also on the probability that they adhere to each other after collision. The rate of particle collisions depends on Brownian motion, differential settling, and fluid shear (refs. 4,5). The rate of disaggregation depends on fluid shear and collisions between particles with sufficient relative translational energy.

In most of the water column, fluid shear is weak and therefore the collision and aggregation of particles is primarily due to Brownian motion and differential settling. However, in certain areas such as at and near the air-water interface, the thermocline, the sediment-water interface, and shallow, near-shore areas where wave action is significant, the fluid shear is large and will have a major effect on aggregation and especially disaggregation of particles.

It should be emphasized that, in the laboratory measurements of particle sizes and settling speeds, there is only one unique condition for the measurement of these quantities, i.e., when they are in a disaggregated state. Since aggregation and disaggregation of particles is a dynamic process that is continually occurring in the laboratory and in the field, the relation of any aggregated state of the sediments in the laboratory to the highly variable states of aggregation in the water column is highly problematical.

Some laboratory experiments have recently been conducted concerned with the dynamics of flocculation of fine-grained sediments in fresh and estuarine waters (ref. 3). These experiments were conducted using a modified viscometer. The particles were initially disaggregated and then placed in the viscometer where they soon aggregated primarily as a result of collisions

caused by fluid shear. A steady-state particle size distribution was eventually reached due to a dynamic equilibrium between aggregation and disaggregation.

Interesting results from these experiments are as follows. (1) For flocs in a particular size range, the time it takes to reach a steady state increases as the floc size increases. (2) For large enough flocs, the number of flocs in a particular size range decreases as the floc size increases. (3) This number decreases as the shear stress increases but is generally non-zero, i.e., there is no maximum floc diameter at any particular shear stress as has been assumed in some modeling of floc dynamics. (4) The number of large flocs per unit mass of sediments decreases as the concentration increases. (5) The density of a floc decreases as the floc diameter increases, as the shear stress decreases, and also as the concentration decreases.

Although these results are interesting, the data from these experiments and others is still insufficient to formulate a quantitative model of flocculation. Much additional work is needed in this area.

ENTRAINMENT AND DEPOSITION

The net flux of sediment at the sediment-water interface, denoted by q_s, can be written as the difference between the entrainment (resuspension) rate E and the deposition rate D, or

$$q_s = E - D \tag{2}$$

Here the assumption has been made that entrainment and deposition are independent processes, i.e., E is the sediment flux when no suspended sediment and therefore no deposition is present, while D is the sediment flux in the absence of entrainment. In the steady state, $q_s = 0$, and the above equation indicates that there is a dynamic equilibrium at the sediment-water interface between entrainment and deposition.

The deposition rate D is relatively easy to describe and will be discussed first. For sediments of uniform size, a reasonable assumption for this quantity is that it is proportional to the concentration, i.e., $D = \beta C$, where β is a coefficient with units of velocity. β can be determined from theoretical arguments (ref. 6) and it can be shown that (a) for particle diameters greater than about 1 μm, β is approximately equal to the settling velocity, and (b) for particle diameters less than 1 μm, Brownian motion is significant in causing deposition and β increasingly deviates from w_s.

As mentioned above, it is important to recognize that, in the usual fine-grained sediment sample found in lakes or oceanic waters, particle sizes

and hence settling velocites vary over several orders of magnitude. In this case, the deposition rate must be approximated as

$$D = \Sigma \beta_m C_m \qquad (3)$$

where the sediments are separated into different components each with its own average particle size, settling velocity, and β.

The description of entrainment is relatively simple for sediments consisting of non-cohesive particles of uniform size and properties. In this case, the entrainment rate E is a function of particle size and applied stress only, i.e., for a specified stress and sediment, the entrainment rate is constant. Denote the total amount of material entrained for a given stress by ε where

$$\varepsilon = \int_0^{\Delta t} E dt.$$

It follows from the above that ε is given by $E\Delta t$, is therefore proportional to the time interval, and becomes infinite as Δt goes to infinity.

For real (especially fine-grained) sediments, the effect on E of particle size variations and cohesion between particles is significant. At low stresses, only the finer particles on the surface of the sediment bed can be entrained while the larger particles are left behind and armor the bed. At any particular stress, this allows only a finite and relatively small amount of sediment to be entrained, i.e., ε is finite as Δt goes to infinity as opposed to non-cohesive, uniform-size sediments where ε is infinite as discussed above. This is the major difference between idealized, non-cohesive sandy sediments and real, fine-grained sediments. At higher stresses, the larger particles can be entrained and this releases the underlying finer particles. But still only a finite amount of material can be entrained at any particular stress.

The entrainment process is further complicated by cohesion of particles and compaction of the bed. These vary with time after deposition and with depth and cause the entrainment rate to vary with time after deposition and depth, e.g., the sediments near the surface are less compacted and relatively easy to entrain while sediments further down are more compacted and more difficult to entrain.

From experimental work (refs. 6-8), it can be shown that for real sediments the parameters on which entrainment depends are at least the following: (1) turbulent stress at the sediment-water interface; (2) water content of the deposited sediments; (3) the composition of the deposited sediments including particle-size distribution, mineralogy, and organic content; (4) vertical

distribution of sediment properties, i.e., manner of deposition of sediments; and (5) activity of benthic organisms. The latter two parameters seem to be less important than the first three, are not quantitatively understood, and will not be considered further here.

As a first approximation based on recent experimental data on fine-grained sediments from Lake Erie and on the ideas summarized above, the following formula for net entrainment is proposed:

$$\varepsilon = a\left[\frac{\tau-\tau_{cr}}{\tau_{cr}}\right]^{m} \qquad \text{for } \tau > \tau_{cr}$$

$$= 0 \qquad \text{for } \tau < \tau_{cr} \tag{4}$$

where

$$a = a_0/t_d^n \tag{5}$$

and ε is the net entrainment/cm^2 of sediment surface, both n and m are approximately equal to two, τ is the shear stress (dynes/cm^2) produced by wave action and currents, τ_{cr} is to be determined from laboratory experiments and is on the order of 1 dyne/cm^2, t_d is the time after deposition in days, and a_0 for fine-grained sediments is approximately 8×10^{-3} but its exact value depends on the particular sediment.

The above formula is for the net entrainment. Of course, the total amount of sediment is not entrained instantaneously but over a period of time on the order of an hour. In numerical computations, if the numerical time step is on the order of an hour or more, the above equations are all that is needed. For time steps less than an hour, information on the entrainment rate is also needed. A reasonable approximation to this quantity is that E is constant and equal to its initial value $E_0 \equiv E(t=0)$ where E_0 is obtained from experimental data. A crude approximation for E_0 is that

$$E_0 = \frac{\varepsilon}{\Delta t} \tag{6}$$

where Δt is one hour. When using this equation, it should be remembered that only a finite amount of material can be entrained. After this amount of material is entrained, the entrainment rate is necessarily zero until of course further sediment is deposited.

In summary, a numerical model of the entrainment and deposition of fine-grained sediments should include at least the following:

(a) Approximation of deposition by at least three components each with its own average β.

(b) Approximation of the net entrainment by Eqs. (4) and (5).

(c) Approximation of the entrainment rate by Eq. (6).

(d) Because the net entrainment and entrainment rate depend on the time after deposition, the sediment bed must be separated into layers each of which has a different average time after deposition and therefore has different properties according to Eqs. (4), (5), and (6). The amount of material in each layer is determined by $\int_0^{\Delta t} q_s \, dt$ where Δt is the time interval, $q_s = E-D$, and E (or ε) and D are determined as described above.

WAVE ACTION AND CURRENTS

Wave action and currents are significant processes when considering sediment transport since (1) they are directly responsible for the transport of sediments; (2) they cause turbulence, which disperses sediments both vertically and horizontally; and (3) they cause a shear stress (resulting primarily from turbulence) at the sediment-water interface which is the primary cause of the resuspension of sediments. Wave action is generally dominant in shallow water, whereas currents are more significant in deeper water. In the Venice Lagoon, currents due to tidal action seem to be the dominant factor.

Considerable work is presently being done on the hydrodynamics of lakes and oceans, including numerical modeling. Numerous reviews on this topic are available (refs. 9-12). Because of this, only a few comments to emphasize what is still needed for accurate modeling of sediment transport will be made.

At present, the most widely used procedures for predicting wave parameters are semi-empirical methods, such as the PNJ method developed by Pierson, Neumann, and James (ref. 13) and the SMB method developed by Sverdrup, Munk, and Bretschneider (refs. 14, 15). These procedures give the significant wave height and significant wave period as a function of wind speed, fetch, and mean depth. From these relations and by assuming inviscid flow, one can determine the horizontal periodic flow at the sediment-water interface. Additional assumptions about the turbulence in this boundary layer at the sediment-water interface then lead to a determination of the bottom shear stress.

The SMB and PNJ methods are semi-empirical in nature, require a great deal of data for calibration, and are therefore difficult to use in regions or conditions for which they are not calibrated. Because of this, wave models presently being developed are more extensively based on the equations of motion, i.e., the energy balance or wave transport equation (refs. 16-18). For deep water, the models have been partially verified and show good agree-

ment with observations for many cases. For shallow water, the models are not as well developed and considerable work is needed in the formulation and verification of these models before they can be generally useful.

Extensive work has been done and is continuing on the dynamics and especially the modeling of currents in lakes and oceans. This is a very active area of research at the present time, and the models, although quite complex, are becoming more and more capable of describing reality. The most general of these models are three-dimensional and time-dependent and include the conservation equations for mass, momentum, and energy.

Two areas of emphasis in improving these models are (1) to make them more realistic by a better description of turbulence, especially in thermally stratified conditions, and (2) to make them more numerically accurate and eificient. In the description of turbulence, many models are incorporating additional equations that describe various turbulence quantities such as a turbulence velocity, a turbulence length, or a turbulence stress-tensor. A more recent emphasis is on the direct numerical simulation of large-scale turbulent eddies accompanied by a low-level model to simulate small-scale turbulence.

In order to make the numerical calculations more accurate and efficient, better algorithms need to be applied. In this context, a particularly annoying problem that has not been solved adequately is the numerical specifications of far field boundary conditions where local disturbances must propagate out of the region without reflection and at the same time disturbances forced by the external flow must be allowed to propagate into the interior region.

CONCLUSIONS

In order to understand and quantitatively model the transport of fine-grained sediments and ultimately the transport of contaminants in the near-shore areas of lakes, estuaries, and oceans processes that must be understood are: (1) particle sizes, settling speeds, and the rates at which particles aggregate and disaggregate; (2) entrainment and deposition; and (3) the hydrodynamics as caused by wave action and currents.

Of these, the modeling of the hydrodynamics has received the most effort and is generally adequate for deep water but needs additional work for shallow water. The treatment of stratified flows and boundary conditions also needs improvement. A considerable amount of work has been done recently on the entrainment and deposition of fine-grained sediments in shallow water. Because of this, the numerical modeling of these processes should improve rapidly in the near future. The least understood of the processes listed above is the aggregation and disaggregation of fine-grained sediments. However, exper-

imental work is being done in this area and our understanding should improve because of this. In summary, considerable work is being done on the transport of fine-grained sediments and contaminants and this should lead in the near future to a quantitative, predictive, numerical method of transport.

ACKNOWLEGEMENTS

This research was supported by the United States Environmental Protection Agency. Mr. Dave Dolan and Dr. Louis S. Swaby were the project officers.

REFERENCES

1 Dickson, K.L., A.W. Maki, W. Brungs, 1985, Fate and Effects of Sediment Bound Chemicals in Aquatic Systems, Proceedings of Sixth Pellston Workshop, Florissant, Colorado, Society of Environmental Toxicology and Chemistry.

2 Bergman, H., R. Kimerle, A. Maki, 1985, Hazard Assessment for Complex Effluents, Society of Environmental Toxicology and Chemistry, Special Publication.

3 Iacobellis, S. 1984, The flocculation of fine-grained lake sediments subjected to a uniform shear stress, M.S. thesis, University of California, Santa Barbara, CA.

4 Smoluchowski, M. 1917, Versuch einer mathematischen theorie der koagulations-kinetik kolloid losungen, Zeitschrift fur Physikalische Chemie 92:129-168.

5 Ives, K.J. 1978, Rate theories, In K.J. Ives, ed., The Scientific Basis of Flocculation, Sijthoff and Noordhoff International Publishers, B.V. Alphensan den Rijn, The Netherlands, pp. 37-61.

6 Lick, W. 1982, Entrainment, deposition, and transport of fine-grained sediments in lakes, Hydrobiologia 91:31-40.

7 Lee, D.Y., W. Lick and S.W. Kang, 1981, The entrainment and deposition of fine-grained sediments in Lake Erie, Journal of Great Lakes Research 7:264-275.

8 Lick, W. and S.W. Kang, 1984, Entrainment of sediments and dredged materials in shallow lake water, Journal of Great Lakes Research, in press.

9 Csanady, G.T., 1982, Circulation in the coastal ocean, Environmental Fluid Mechanics Monographs, D. Reidel Publishing Co., Boston.

10 Cheng, R.T., J.M. Powell and J.M. Dillon, 1976, Numerical models of wind-driven circulation in lakes, Applied Mathematical Modelling 1:141-159.

11 Lick, W., 1976, Numerical modeling of lake currents, Annual Review of Earth Planetary Science 4:49-74.

12 Simons, T.J., 1979, Hydrodynamic models of lakes and shallow seas, Canadian Centre for Inland Waters, Burlington, Ontario.

13 Pierson, W.J., G. Neumann and R.W. James, 1955, Observing and forecasting ocean waves by means of wave spectra and statistics, U.S. Dept. Navy, Hydrography Office, Publ. No. 603, Washington, D.C.

14 Sverdrup, H.U. and W.H. Munk, 1947, Wind, sea, and swell: Theory of relations for forecasting, U.S. Dept. Navy, Hydrography Office, Washington, D.C.

15 Bretschneider, C.L., 1958, Revisions in wave forecasting: Deep and shallow water, Proceedings of 6th Conf. ASCE Council on Wave Research, U.S. Army Coastal Engineering Research Center, Ft. Belvoir, VA, pp. 30-67.

16 Barnett, T.P., 1968, On the generation, dissipation and prediction of ocean waves, J. Geophys. Res. 73:513-530.

17 Hasselman, K., 1978, On the spectral energy balance and numerical prediction of ocean waves, In: A. Favre and K. Hasselman, eds., Turbulent Fluxes Through the Sea Surface, Wave Dynamics, and Prediction, Plenum Press, New York, pp. 531-596.

18 Gunther, H., W. Rosenthal, T.J. Weare, B.A. Worthington, K. Hasselman and J.A. Ewing, 1979, A hybrid parametrical wave prediction model, J. Geophys. Res. 84:5727-5738.